→ THE SEEDS OF DISRUPTIVE INNOVATION

ESA's Advanced Concepts Team

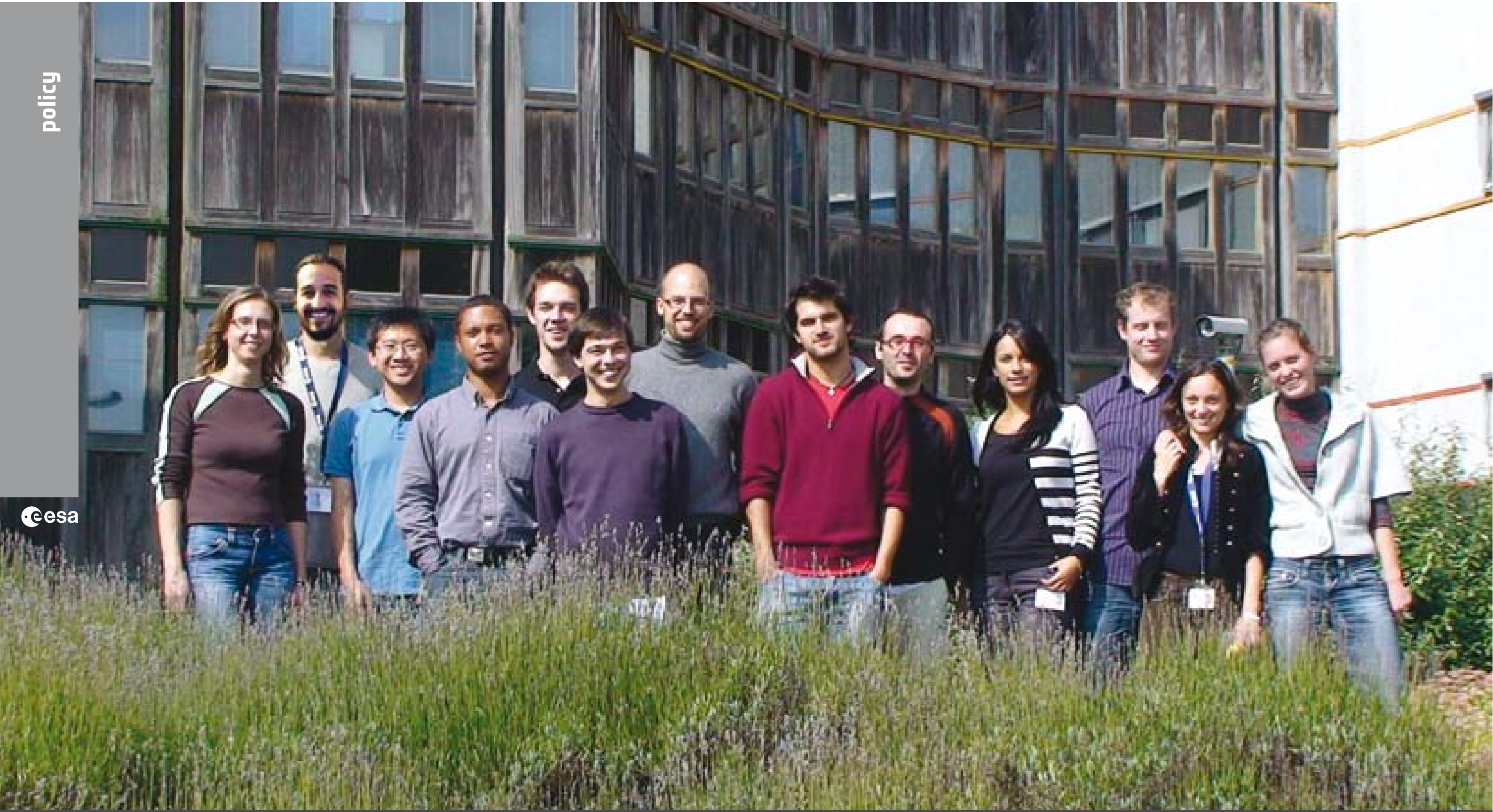
Leopold Summerer & Dario Izzo
Future and Strategic Studies Office, DG's Policy Office, ESTEC, Noordwijk, The Netherlands

Géraldine Naja & Isabelle Duvaux-Bechon
DG's Policy Office. ESA Headquarters, Paris, France

Space activities will likely be very different in the future, influenced by innovation in sectors and areas that are not necessarily on the 'radar screens' today of space agencies and industry. By creating, maintaining and evolving the Advanced Concepts Team, ESA continues to innovate and to show the way to prepare for potentially disruptive changes.

In 1930, Frederick Edwin Smith, First Earl of Birkenhead, the former UK Lord Chancellor and one of the best friends of Sir Winston Churchill, published a book called *The world in 2030*. He started his preface with: "If one looks back a hundred years and in so looking compares the world of that day with the world of today, one becomes almost equally conscious of the equal risk of underestimating and of overestimating the developments which lie in front of us. That man only is wise who does not dogmatise and who proclaims nothing impossible."

Some of his predictions have indeed become true already, but others are still to be realised, even though very few actually sound entirely unrealistic. Daring to think differently, not accepting dogmatic truths and not being bounded by the heritage of past solutions while remaining solidly grounded in the realm of science are key to such an exercise. This is also true for any attempt that focuses not on incremental or sustaining changes, but also radical and potentially disruptive ones.



↑ The ACT in September 2010, left to right: Fairouz Nasr, Francesco Biscani, Chit Hong Yam, Joris Olympio, Frazer Barnsley, Luis Simoes, Leopold Summerer, Eduardo Martin Moraud, Dario Izzo, Loretta Latronico, Duncan Barker, Giuseppina Schiavone, Cynthia Maan

ESA's Advanced Concepts Team (ACT) is not about predicting the future, nor about 'future science', 'futurism' or 'futurology'. The ACT is about contributing to the preparation of ESA and the European space sector for different futures. In this sense, our team tries to follow the French writer and aviator Antoine de Saint-Exupéry, when he said, "As for the future, your task is not to foresee it, but to enable it."

How do we work?

The ACT was created in 2002 with the explicit mission to 'monitor, perform and foster research on advanced space systems, innovative concepts and working methods'. As part of its goal, the team has to deliver rigorous and rapid assessments of advanced concepts that are not necessarily yet linked to space.

Preparing for the future is nothing new. We all prepare for our futures, and it is done in almost every successful organisation. So what is different about the ACT? The long lead and operational times of space projects, preparing for the 'future' of the space sector means looking further into the unknown than in probably any other sector: the current programmatic horizon of the space sector is already extending 10 to 15 years ahead, substantially longer than most other industries.

Preparing missions and technologies to be launched in a few years and which are designed to remain not only operational, but also competitive, with fast-evolving terrestrial alternatives for a decade and longer is in itself a fantastic challenge. Every part of ESA and the space sector must stay abreast of latest developments in its core technologies.

> **He who innovates will have for his enemies all those who are well off under the existing order of things, and only lukewarm supporters in those who might be better off under the new.**
>
> Niccolò Machiavelli

History has shown, however, that large and especially successful organisations are particularly prone to either failing to recognise or to underestimating the impact of initially small developments that appear on the fringes of their core activities. Such organisations risk being taken by surprise once their core market is affected by what scholarly literature calls 'disruptive innovation'.

With current programmatic horizons extending already 10 years ahead and limited possibilities to introduce new technologies in late phases of space projects, the preparation for over-the-horizon futures requires not only understanding and extrapolating current trends and their interactions, but also anticipating upcoming new evolutions that are still in their very infancy today. It is therefore important to create a structure and mechanisms where these weak early signs of upcoming changes can be detected, researched, analysed and interpreted. As the principal actors for extending general knowledge, universities are common birthplaces and 'hotbeds' for such signs and provide 'sandboxes' for their early stages. Tapping into these and intelligently extracting useful information for the future of the space sector is how the team contributes to the preparation of the future of ESA.

Therefore the team's work is deliberately not within a specific programmatic or technical context, but looking outside the traditional scope of ESA, further into the future as well as outside of the thematic areas of space.

When deciding how to structure our team, it was natural to learn from other innovation leaders, taking into account what was working well and benefiting from lessons learned. An analysis was carried out of the approaches adopted by the NASA Institute for Advanced Concepts (NIAC was operational form 1998 to 2007 and has just recently been re-established in a slightly different configuration as part of the office of the NASA Chief Technologist in 2010.), DARPA, the central research and development organisation in the US Department of Defense, the MIT Medialab, Starlab, Lockheed's Skunk Works and some of its imitators, as well as the set-ups of highly innovative companies such as Google, IBM and others.

Based on this analysis, the following key aspects of a successful implementation were identified:

- Interdisciplinarity is a key requirement since most 'game-changing' developments emerge and progress initially on the fringes and intersections of disciplines.
- Regular renewal of personnel is beneficial to keep such teams on the leading edge.
- Taking risks needs to be encouraged and rewarded.
- Scientific rigour and competence is key to avoid drifting into the realms of science fiction.
- Clear support from top-management, without which such groups struggle to survive, especially in successful organisations. Such teams and activities tend to be ridiculed, admired, not taken seriously or seen as a threat by the core of the establishment – depending on relative interests at stake.
- Close ties with academia are important. While small and medium-sized enterprises and start-up companies seem to be key for disruptive innovation in a 5–10 year time-span, the most relevant ideas and concepts for longer than 10–15 years are generated within academia and research centres.

Implementing these within the possibilities of the ESA environment, led to the following main parameters of the ACT.

The team was set up as a group of researchers, mainly research fellows (post-doctoral researchers joining the team for two years) and young graduates (recent master's-level graduates joining the team for one year),

→ The Advanced Concepts Team (ACT)

This technical corporate research 'think tank' within ESA's Future and Strategic Studies Office, is exploring advanced concepts, techniques and working methods that are beyond the horizon of regular ESA activities and projects.

It is an integral part of the preparation of the future of and for ESA, coherent and consistent with the General Studies Programme. Our team relies on the interdisciplinary cooperation of a dynamic group of young researchers, who join the group for one to two years as part of their academic career, thus adding constantly new competence and a fresh standpoint to the team and ESA.

Our research areas currently covered are: biomimetics, fundamental physics, computer science and applied mathematics, mission analysis, computational management science, artificial intelligence and advanced energy systems. These themes evolve over time and the teams' competence base and its topics are constantly adapted to the evolving needs of ESA.

Internal and collaborative research with academia are at the core of the ACT activities, providing the basis for those activities related to opening the horizon of ESA towards new areas, offering an entry point for innovative academic research ideas, bridging these to operational technical expertise and deriving trends and strategic directions from research progress.

who originate from a broad variety of academic fields and are aiming at an academic career. The pursuit of highest scientific standards is therefore as much in their own interest as it is in the interest of the team. The steady renewal of researchers (one- or two-year periods within the team) allows a continuous, flexible adaptation of our team's competence base to the needs of ESA and to evolutions in science and technology. It is also the basis for fresh unbiased assessments and re-evaluations, while avoiding, empire-building, and preventing ESA-career considerations from influencing the orientation and conduct of research.

Consequently and contrary to classical approaches, the management of the team consists essentially in providing the right frame conditions, strategic perspectives, ensuring consistency and quality, putting the research into a larger context and interfacing with external groups but not on directing the individual researchers and their research activities. Externally, we interact almost exclusively with universities and specifically small, innovative research labs, often with no prior link to ESA or the space sector.

Based on the success models of other innovation leaders, administratively, we have always been situated at corporate level, outside the missions and programme and support directorates, and independent from the core technical strategies and 'road-maps'. Originally the team was created as an integral part of the ESA General Studies Programme (GSP) and is currently contributing to the goals of the GSP. Together with the GSP, we sit in the Future and Strategic Studies Office, itself part of the Director General's Policy Office of ESA.

As far as is known, the combination of temporary in-house researchers from a multitude of disciplines, the reliance on empowered young researchers who are encouraged to propose and relatively free to pursue new ideas, together with the framework to perform collaborative research in ad-hoc virtual teams, is quite unique and innovative in itself. The value of this combination has been recognised internationally and some initiatives have emerged at national level inspired by the ACT model.

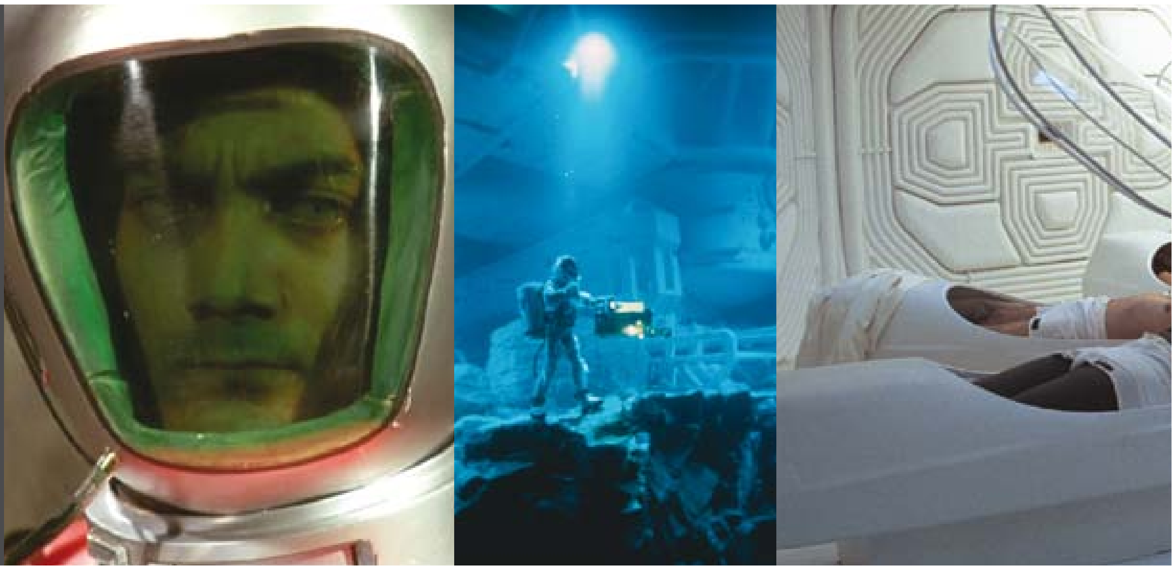
What topics do we look at?

The research directions of the group come from three sources: the daily team activities, which naturally provide a detailed outlook on advances and trends in research, from discussions within the Director General's Policy Office and from the interaction and discussions with the rest of ESA. To stimulate innovation and creative thinking, ACT members are asked to continuously propose new ideas and research subjects and are encouraged to dedicate a certain percentage of their time on new, self-defined topics.

We have one 'golden rule': whenever something is done by anyone else within ESA, it becomes 'off-topic' for us, and we move on to new areas. In practical terms, via our

→ The team and the Advanced Concepts community

Similar to one of the goals of ESA's Young Graduate Trainee programme (sponsoring young graduates in a space discipline and providing them with a good working knowledge of ESA for a career in the European space industry) but focusing on academia and research institutes, ACT researchers (who originate mainly from non-space related fields) pursue their academic careers after leaving the team with a better knowledge of ESA's needs and of the space sector in general.



→ Ideas we have seen in popular science fiction are not always far from possibility. Liquid breathing, seen in TV's UFO (1970) and the movie The Abyss (1989), and human hibernation, in the movie 2001: A Space Odyssey (1968) and Alien (1979), and many other concepts like these are studied by ACT, either to debunk flawed 'breakthroughs' or to assess their feasibility

> **The term 'disruptive innovation' is used in business and technology literature to describe innovations that improve a product or service in ways that the market does not expect.**

research, we act as a cross-departmental 'pathfinder' to explore novel or potentially promising areas for ESA and the space sector, ranging from applied to basic fundamental ones.

These are generally:

- concepts and techniques from areas with no current links to the space sector (e.g. biomimetic approaches to engineering, brain/machine interfaces, liquid breathing, curiosity cloning, peer-to-peer computing, crowd-sourcing gaming, innovation diffusion and dynamics);
- emerging directly from recent, cutting-edge basic scientific research (e.g. mathematical global optimisation techniques, cloud-based uncertainty modelling, helicon thrusters, pure general relativistic approach to GNSS constellation design, vibrating systems in general relativity, 'metamaterials' in the optical frequency range, distributed/swarm intelligence);
- areas where ESA is likely to build up competence but is hesitating due to the lack of concrete short-term programmatic needs (e.g. space nuclear power sources, asteroid deflection or planetary protection research; and
- far-reaching subjects in which ESA is expected to have a technically solid position but which are too immature to be taken up by regular ESA programmes or projects (e.g. solar power from space, use of hypometabolic states for space travel ('hibernation'), asteroid deflection, active removal of space debris, novel working methods based on new IT tools such as virtual collaborative environments, 'terraforming' and 'geoengineering').

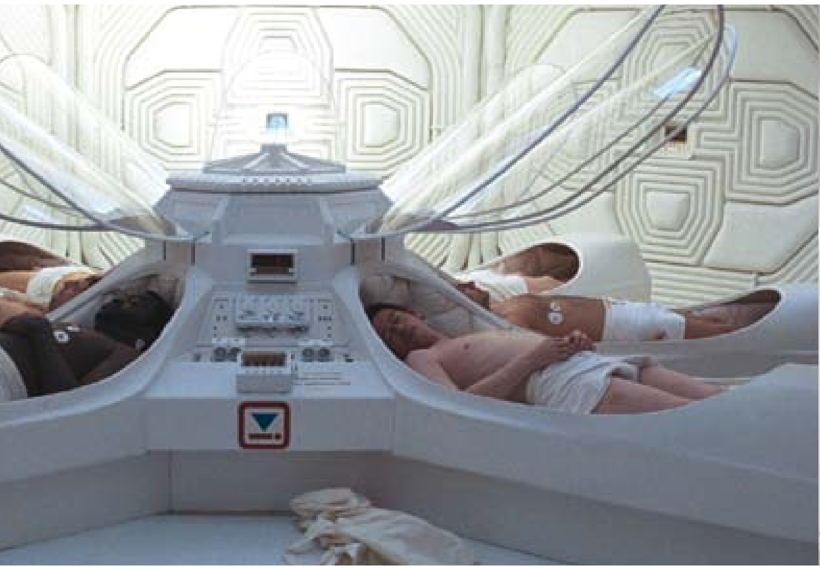
Many of these subjects require skills that are not readily available in other parts of ESA.

ACT research

Most of our research is performed within the team in small subgroups. If a subject requires additional expertise not readily available within the group or within ESA, the topic is proposed for a collaborative study together with researchers from European universities via the Ariadna scheme.

In conducting their research, ACT members take advantage of a unique environment, which offers:

- Strong links with European universities. Researchers typically arrive to the ACT directly from their universities and the work in the team offers them the opportunity to consolidate and broaden their links with the academic world. A continuous feedback from the



academic community is thus available to stimulate and improve the outcome of the team research activity. Special links are maintained with the former members of the team (ACT community).

- Interdisciplinarity of the team. The daily exchange of ideas with people having radically different research and personal backgrounds, stimulate the individual ACT member to transversal thinking, setting a fertile ground where innovative thinking can grow.
- Direct contact with ESA scientists and engineers. Working at ESTEC, research fellows usually establish relatively quickly personal contacts with ESA staff in the field of specialisation closest to theirs. This provides them with direct insight into the ongoing developments in the space sector as well as its expected future needs. Furthermore it also allows an uncomplicated, personal information exchange and link to other ESA teams preparing the future.

For the benefit of ESA and the European space sector

Some of the activities of the ACT are oriented to providing a critical analysis on technical subjects for which a specific knowledge does not exist in any ESA directorate, or for which appropriate manpower is not rapidly available. This has the effect of anticipating ESA needs by providing 'entry points' to potentially disruptive ideas (e.g. neuromorphic computing, dual-stage four-gridded ion thrusters (DS4G), distributed evolutionary computing and 'space tourism') while at the same time debunking flawed 'breakthroughs' (e.g. assessment of breakthrough propulsion concepts from a theoretical physics standpoint).

↓ A very new concept in electric propulsion, the Dual Stage Four-Gridded (DS4G) ion thruster for interplanetary spacecraft, was successfully tested in 2005 by ESA and the Australian National University

→ Ariadna: A framework for advanced cooperative research

Ariadna is an initiative aimed at establishing stronger links with the European scientific community by carrying out joint research projects between the ACT and selected academic institutions. During Ariadna projects, researchers from European academia explore, together with ACT researchers, some emerging fundamental questions as defined by the ACT in an Ariadna Call for Proposal. Universities have also the possibility to propose their own research ideas if relevant to a larger theme described in an Ariadna Call for Ideas. A short description of the results obtained in each Ariadna project can be found in the Ariadna brochure, available on the Ariadna web site (www.esa.int/ariadna).

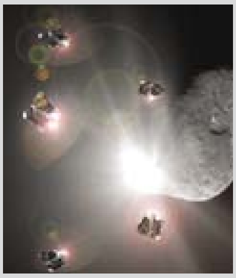
Since the first studies in 2004 and until end 2009, the team has studied 54 different topics together with universities institutes, on average nine new topics per year. Since some of these research projects, especially the high-risk ones are done in parallel studies with different departments, 78 Ariadna studies have actually been performed.

Disruptive changes normally emerge when disciplinary boundaries are crossed and concepts and techniques are applied out of their context (e.g. Google Earth and Earth observation data, participatory networks of news/media content generation versus centrally organised one-way communication). Therefore, one of the most important qualities of a 'think tank' is its interdisciplinary nature – and this is experienced in the ACT as an integral part of their daily work. The research done by the team is thus planting the seeds for 'disruptive innovation' in the European space sector and at the same time trying to keep ESA alert of potentially disruptive innovation emerging on the fringes of the traditional space sector.

From short reports responding to needs of policy and decision makers, documents analysing trends and advances in niche areas potentially interesting for ESA (e.g. space tourism) to hands-on trials of new ways of working in ACT (e.g. Web 2.0 methods for internal organisation, group and data management), ESA benefits from the essential independent and objective way of thinking of a team made up of constantly renewed young researchers unconstrained by an ESA career-oriented approach.

ACT researchers are encouraged to take some substantial risk with their research topics and concepts and not all of the research of the team leads to tangible results that can be taken up by other parts of ESA. Some projects

Ariadna Study Titles:



Mission analysis

- Advanced global optimisation tools for mission analysis and design
- Study on libration points of the Sun and the interstellar medium for interstellar travel
- Assessment of mission design including utilisation of libration points and weak stability boundaries
- Feasibility study for a spacecraft navigation system relying on pulsar timing information
- Electrostatic forces for satellite swarm navigation and reconfiguration
- Spiral trajectories in global optimisation of interplanetary and orbital transfers
- The 'Flower Constellation Set' and its possible applications
- Space webs
- Global trajectory optimisation: Can we prune the solution space when considering deep space manoeuvres?
- Asteroid centrifugal fragmentation
- Dynamics and stability of tethered satellites at Lagrangian points
- NEO Encounter 2029: Orbital prediction via differential algebra and Taylor models
- NEO Encounter 2029: 'Mirror bees' concept for asteroid deflection
- NEO Encounter 2029: Determination of asteroid fragmentation energy from an impactor and post-fragmentation dynamics

Biomimetics

- EAP-based artificial muscles as an alternative to space mechanisms
- Biologically inspired joints for innovative articulations concepts
- Bio-inspired distributed system for thermal (or particles) transport
- Strain sensors inspired by campaniform sensilla
- Attaching mechanisms and strategies inspired by spider legs
- Bio-inspiration from plant roots
- Neuromorphic computation of optical flow data
- Quantifying the landing reaction of cockroaches
- Path planning strategies inspired by swarm behaviour of plant root apexes

Bioengineering

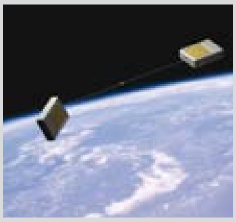
- Mammalian hibernation mechanisms: Relevance to a possible human hypometabolic induced state
- Curiosity cloning – Neural modelling for image analysis
- Non-invasive brain/machine interfaces
- Machine/animal hybrid controllers for space applications

Fundamental physics

- Theoretical study of the interaction of mesoscopic systems with gravity
- Lorentz-invariant description of the Feigel process for the extraction of momentum from a vacuum
- A search for invariant relative satellite motion
- On the effect of the global cosmological expansion on the local dynamics in the Solar System
- Non-perturbative effects in complex gravitationally bound systems
- Mapping the spacetime metric with a global navigation satellite system

Energy systems

- Laser power-beaming feasibility: Non-mechanical beam-steering options, laser phase-locking and control
- Environmental impacts of high-power density microwave beams on different atmospheric layers
- Sponge iron process for manned space exploration
- Biomass-based fuel cells for manned space exploration



Propulsion

- Helicon Double Layer Thruster concept for high-power NEP missions
- Open magnetic fusion for space propulsion
- Numerical simulation of the Helicon Double Layer Thruster concept
- Advanced concepts of electromagnetic generation, confinement and acceleration of high-density plasma for propulsion
- Advanced injectors for chemical rockets inspired by ink-jet printing technology
- 'On-a-chip microdischarge thruster arrays' inspired by photonic device technology for plasma television
- Understanding of the physics and numerical simulation of Helicon Double Layer Thruster concept
- Electrodynamic tether microsats at the giant planets

Nanotechnology

- Microstructured radiators
- Metamaterials for space applications

Artificial intelligence

- Natural language techniques in support of spacecraft design
- Evolution in robotic islands: Enhancing the potential of automatic design techniques through a parallel distributed environment
- Evolving a collective consciousness for a swarm of pico-satellites

Computer science

- Efficient use of self-validated integrators for space applications
- Application of clouds for modelling uncertainties in robust space system design
- Assessing the accuracy of interval arithmetic estimates in spaceflight mechanics
- 'Gossip-based' strategies in global optimisation

end with 'just' an academic knowledge gain in form of a publication, others are shelved if the analysis reveals that the original idea was not as promising as initially expected or others turn out to be too far-fetched to warrant further investigation at this stage. Similar to venture capital seed funding, only a few of the concepts developed by the team are expected to make significant changes and have an impact in the space sector.

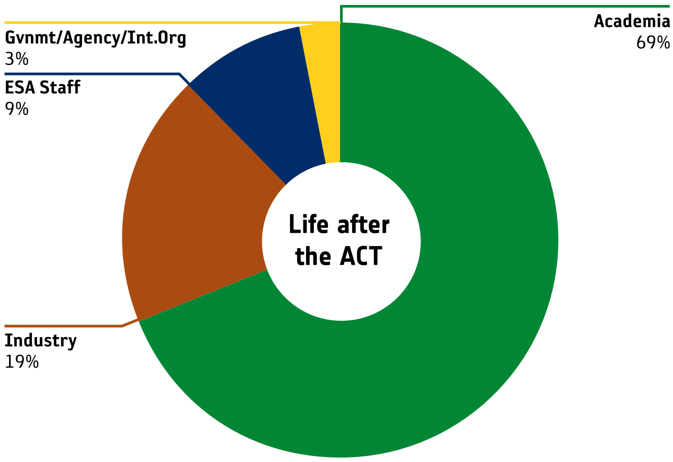
Since we are operating in an academic way, publishing all our research and encouraging feedback, ideas and concepts are not only taken up by ESA, but also by external researchers. These could take the form of small programmes funded further at national level (e.g. tether research in Spain, space webs in Scotland and Sweden, further development and testing of the four-grid ion thruster in the UK), concepts taken up by start-up companies (e.g. metalhydride fuel cells) or large EU framework programme activities (e.g. €3.5 million 'helicon' thruster EC FP7 activity directly based on a €25 000 Ariadna study).

ESA also derives some substantial indirect benefit from these activities with research groups having no prior link to the space sector. Often, universities are surprised by the interest of a space agency in their research, and thus continue their work after such contacts with a better understanding of the space sector and its requirements.

Publications

As for all research teams, the feedback from peers and the international research community is very important for us. In total, we published 349 scientific documents (between 2002 and August 2010). These include 65 peer-reviewed single articles, 7 book chapters, 3 books, 182 conference papers and 92 other publicly available scientific documents (essentially research project reports). The steady increase of the ratio of peer-reviewed publications (including books and book chapters) to all scientific publications we authored can be seen as indicating an increase of the overall quality of ACT-authored publications (increase from 17% in 2002 to 48% in 2009).

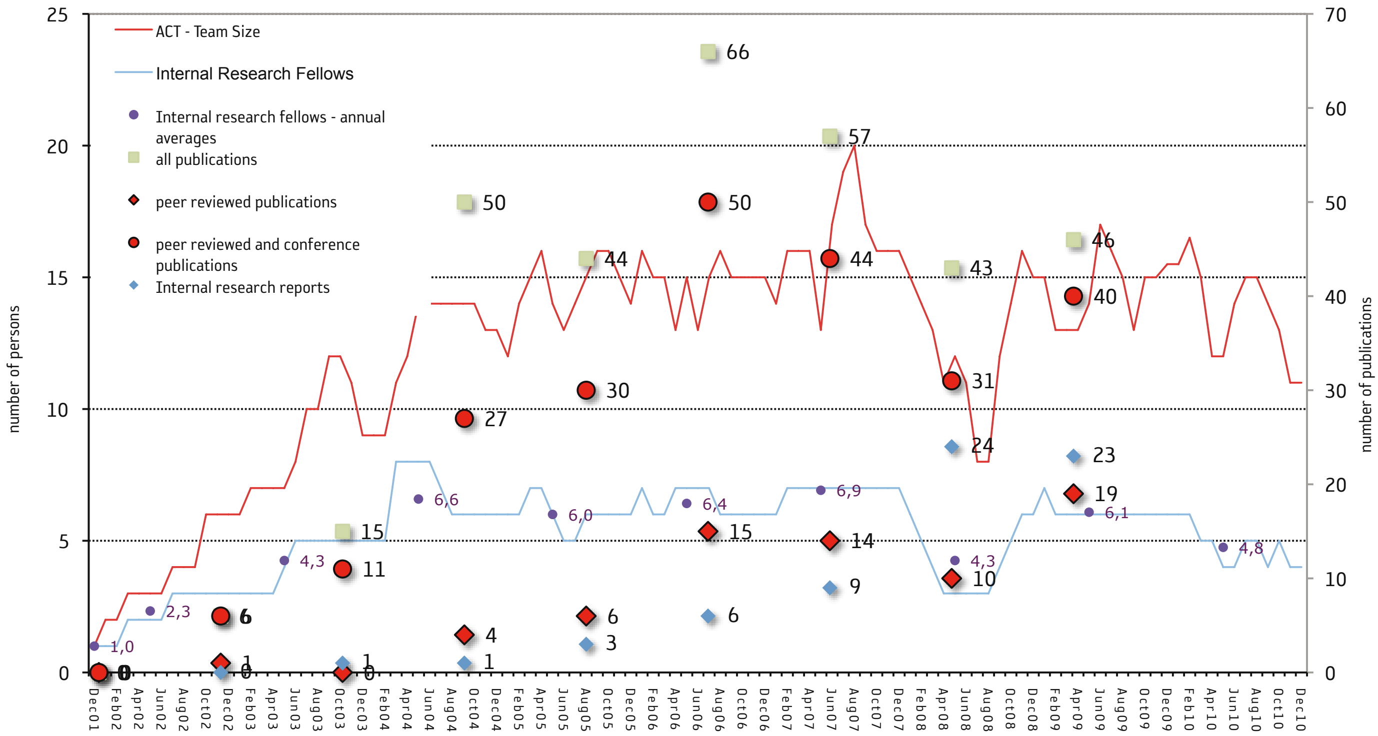
Links to all ACT publications are available on web-based database at the ACT website (**www.esa.int/act**)



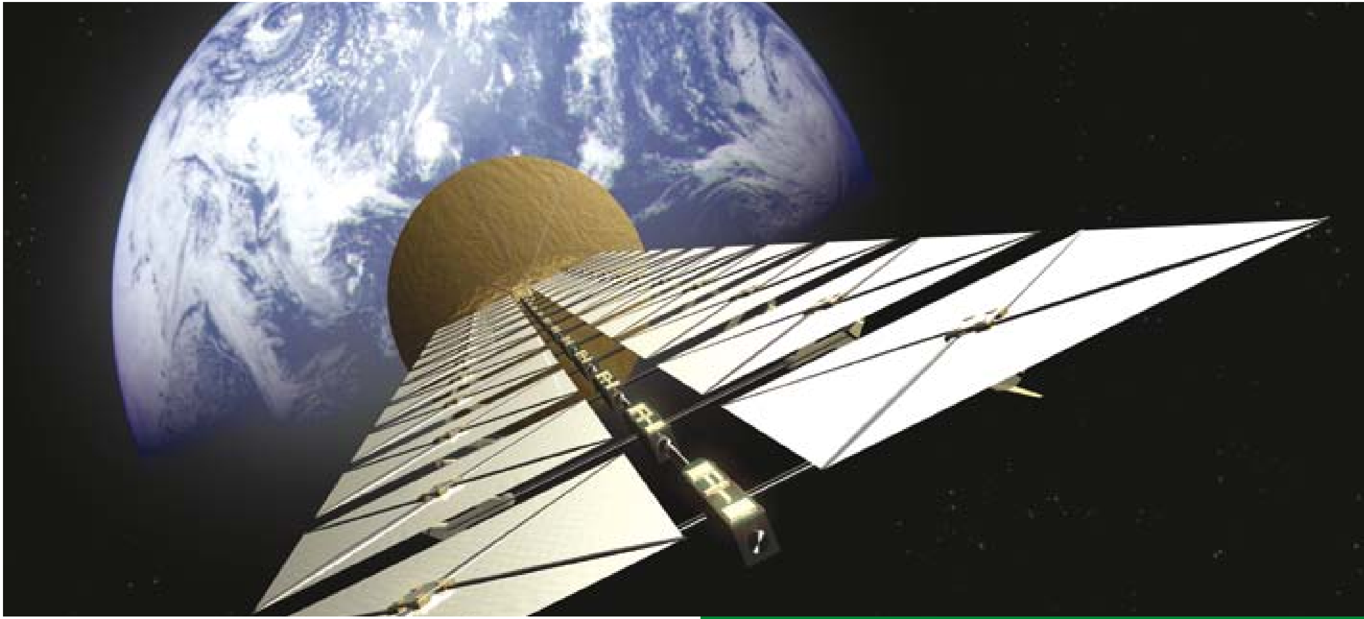
↑ Life after leaving the team: post-ACT affiliations

Research network

We can only host a limited amount of in-house expertise. An active network of universities and external researchers is therefore important to achieve its goals and since the topics of the team are located on the fringes of space activities and beyond these, such a network includes many research centres not specialised in space. This has turned out to be itself a valuable asset, especially since the space sector has for a long time been thought of as a 'lonely forerunner' and experienced difficulties in engaging and cross-fertilising with other sectors.



↑ Evolution of the ACT publications record, per research fellow (RF) , with data until and including 2009



This research network is neither static nor fixed, but evolving with the team, its orientations and its members. One quantitative way to measure its size is represented by the 444 unique co-authors of publications published by the team (available at **www.esa.int/gsp/ACT/publications**)

These are people who have actively worked with one or several researchers of the team in a successful project that led to a publication. It is therefore a conservative low estimate; the number of actual research contacts and loose co-operations is higher. Since practically all members of the team are temporary researchers, the alumni network is constantly growing. 69% of ACT members go back to academia immediately after leaving the team and of all the team members 54% are at time of writing still within an academic career.

Hic futura parantur...

Here we prepare the future. Detecting the signs that announce changes and opportunities to come, understanding their importance and performing research on them with a view to take full advantage for ESA and the European space sector, is a daunting task. The secret lies in persisting to innovate and take risks, to challenge the status quo and to continue to seek new ways to do things, new concepts and new solutions. While space will remain essentially the same, the scope, purpose and type of our use of space and our activities in space are likely to be very different. With its innovative way of operating, the Advanced Concepts Team helps ESA and the European space sector to not only foresee, but also to enable our future in space.

Further reading

- *The World in 2030*, The Earl of Birkenhead, Hodder and Stoughton, London 1930
- *The Innovator's Dilemma*, Clayton M. Christensen, Harvard Business School Press, Boston 1997
- *The Innovator's Solution*, Clayton M. Christensen and M. Raynor, Harvard Business School Press, Boston 2003

JAPANESE CLOTH

Deploying very large structures

The idea of generating large amounts of carbon-free energy in space by harvesting solar radiation and wirelessly transmitting power to Earth had already been described by the early space visionaries of the first half of the 20th century before a first engineering concept was published in 1968.

We analysed the general validity of these concepts compared to terrestrial alternatives and worked especially on the integration of space and terrestrial-based solar power plants. All of these concepts rely on the deployment of relatively homogeneous very large structures in space, a technology for which there is equal interest from many other space applications, such as very large antennas. As an example of our hands-on research activity, we participated in the Japanese 'Furoshiki' sounding rocket experiment (named after a traditional Japanese wrapping cloth), launched by JAXA in 2006.

This experiment deployed a 130 m^2 net in microgravity. The European contribution was two small robots, which moved on the deployed net simulating the movement of future phased array microwave antenna elements. Following this experiment, conducted together with the universities of Tokyo, Kobe and the Vienna University of Technology, the team has studied together with the Universities of Glasgow and Stockholm (KTH) the dynamics of very large nets rotationally deployed in microgravity. A second sounding rocket experiment to test such a deployment is currently in preparation at these universities.

MASS INNOVATION

Open source development of a massively parallel engineering optimisation platform

'Mass innovation' is a relatively new term indicating a process of creative thinking based on modern media resources to organise and increase the communication flow within the largest possible interested community. Being a novel path to innovation, and previously unavailable because it is based on technology that was created only recently, mass innovation has attracted the interest of many groups seeking to control and channel it towards synergies with corporate core businesses. In an effort to better understand the potential of this innovation process, we have been experimenting for four years with open source software developments.

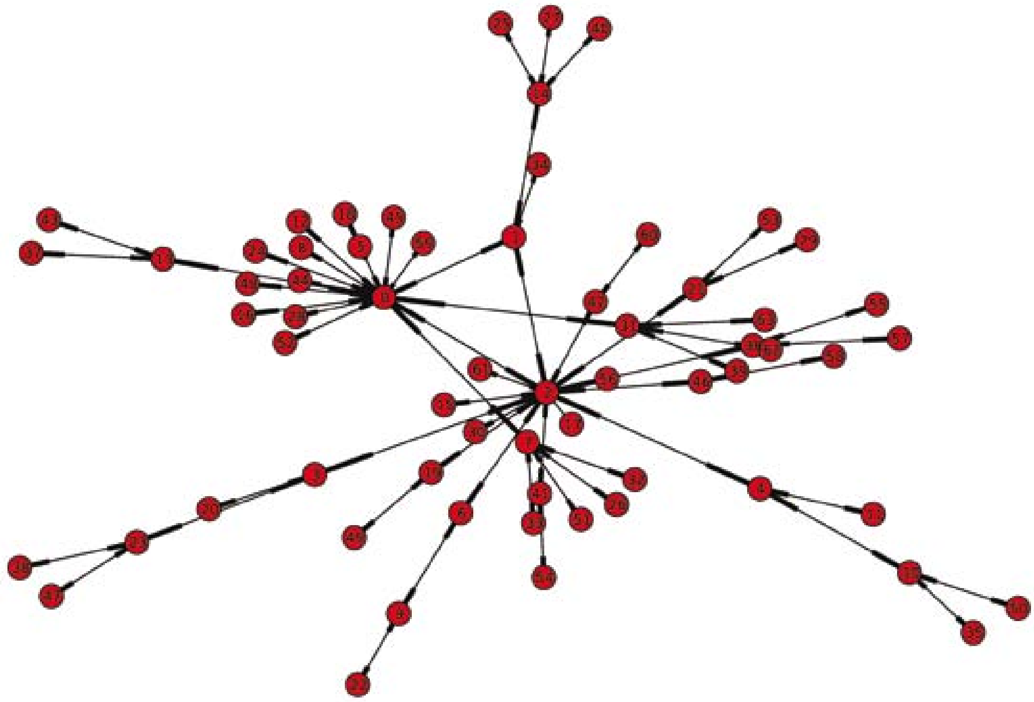
One of four projects looked at by our team is the 'Parallel Global Multiobjective Optimiser' (PaGMO). It was developed to benefit from the increasing availability of large computer CPU clusters and to allow engineers and scientists to take full advantage of these new massively parallel and distributed architectures. The guiding principle is to let the scientists focus on defining their optimisation problem, while the code first takes care of making the optimisation process 'massively parallel' efficiently, taking full advantage of the underlying network of CPUs, and then defining the optimisation strategy.

According to the problem type, the PaGMO can use a number of algorithms, including 'meta-heuristic' techniques, such as ant colony or genetic strategies, but also more classical approaches based on sequential quadratic programming or interior point methods. Solutions to the problem, as defined by the user, migrate among different instances along an underlying topology defined over the CPU network.

The team has successfully used the PaGMO in a number of projects, including ionospheric data processing, inverse engineering of micro-structured radiators, evolution of robotic neuro-controllers in niche island populations and the optimisation of interplanetary trajectories (during its participation to the Global Trajectory Optimisation Competitions).

In 2010, the PaGMO was accepted as an open source project to participate to the Google initiative 'Google Summer of Code' alongside projects such as Ubuntu, Open Office, Facebook and others.

→ Various aspects of the behaviour of ants and ant colonies are used in computer science and operations research for solving computational problems. A scale-free topology in PaGMO (here the Barabasi-Albert model is used to grow the network). Each node represents a CPU and the arrows represent possible migration routes for solution (design points) being optimised by different techniques/algorithms



INSPIRED BY INSECTS

A neuromorphic approach to spacecraft landing

The term 'neuromorphic', referring to electrical circuits, was first introduced to indicate devices mimicking neurobiological circuits and copying the functions of a biological system. The resulting devices are often created either in analogue or digital integrated circuits (very large-scale integration system or field-programmable gate arrays) and are characterised by low power consumption and reduced mass. Because of the biological origin of the principle used in neuromorphic circuits, information of interest at a behavioural level (i.e. control and guidance) are often extracted directly and without any further processing. Thanks to these particularities, neuromorphic chips have found applications in fields such as prosthetic medicine and visual guidance of 'micro air vehicles'.

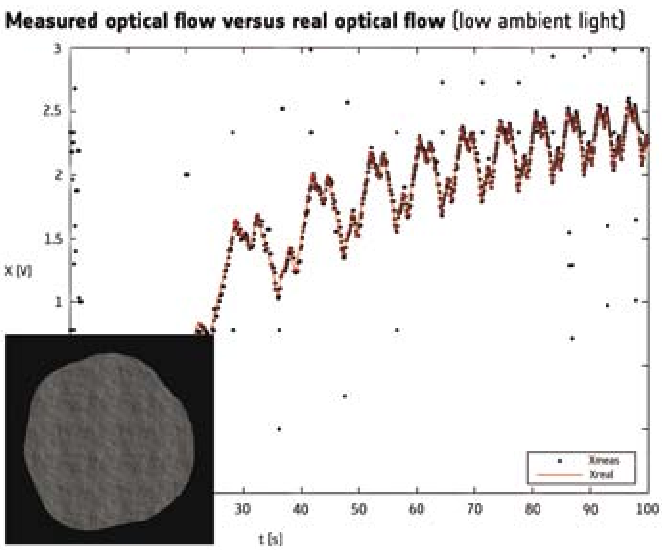
We have been working on elementary motion detectors, a simple neuromorphic neural circuit able to measure directly the optical flow inspired by insects. Insects rely on elementary motion detectors at a behavioural level to guide their flight and landing. For example, honey bees land on flat surfaces using only a small part of the roughly 950 000 neurons at their disposal by simply keeping the ventral optical flow constant.

We needed to answer two questions:
Can such detectors be used in the illumination conditions you would experience while landing on the Moon, on Mars or on an Earth co-orbiting asteroid?

Is the principle of constant optical flow landing, evolved in nature for insect flight, convenient at some level also for guiding the landing of a spacecraft (i.e. a system equipped with reaction propulsion and designed to make efficient use of its mass)?

In collaboration with ETH/UZH in Zürich and the Université de la Méditerranée in Marseille, the team used artificial though realistic images of planetary surfaces to characterise the elementary motion detector performances during simulated landings on the Moon, on Mars and on virtual asteroids. Results show a very good and extremely uniform performance of the optical flow sensor with respect to lightning conditions. The results obtained served as the basis for the development of fully automated autopilots and navigation algorithms for both guidance and navigation during a planetary landing based on these detectors.

In parallel, we used the mathematical theory of optimal processes to compare the control structure of constant optical flow planetary descents with the structure of the optimal control of normal descents. The results show how constant optical flow descents, while able to closely approximate minimum-time optimal trajectories, fail to do so for maximal final mass trajectories, introducing a propellant mass penalty (evaluated at around 5–10% for 'high-gate/low-gate' Apollo-like descents) that need to be traded off with the expected hardware and software simplification offered by such a bio-inspired architecture.



↑ Example of the performance of one of the elementary motion detectors studied (from the group at the Université de la Méditerranée in Marseille) during a fast spiral descent on a virtual asteroid (lower left corner) under critical lighting conditions as simulated using the software PANGU. Light direction is assumed for simplicity to be always at zenith. The total avionics payload of the sensor would have a mass of less than 10 g and consume less than 1W of power.